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Climate Change, Industrial Transformation, and "Development Traps"

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Abstract

This paper examines the possibility of environmental "development traps," or "brown poverty traps," caused by interactions between the impacts of climate change and increasing returns in the development of "clean-technology" sectors. A simple specification is used in which the economy can produce a single homogeneous consumption good with two different technologies. In the "old" sector, technology has global diminishing returns to scale and depends on the use of fossil energy that gives rise to long-lived, damaging climate change. In the "new" sector, the technology has convex-concave production and is not dependent on the polluting energy input. If the new sector does not grow fast enough to move through the phase of increasing returns, then the economy may linger at a low level of income indefinitely or it may achieve greater progress but then get driven back down to a lower level of income by environmental degradation. Stimulating growth in the new sector thus may be a key element for avoiding an environmental poverty trap and achieving higher, sustained income levels.

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CLIMATE CHANGE, INDUSTRIAL TRANSFORMATION, AND “DEVELOPMENT TRAPS”[1]

1. INTRODUCTION

For more than 80 years, economists have used variants of the model first proposed by Frank Ramsey to study the sources of overall economic growth (Ramsey, 1928; Solow, 1956). Early versions of the model focused on how savings by households, invested into increasing the overall stock of physical capital, could increase income per capita over time under different sets of circumstances for the productivity of capital and labor, the willingness to save for future consumption versus consume today, and the rate of population growth. Over the decades, substantially more sophisticated models have been developed – including, most notably for our purposes in this paper, literature incorporating interactions between economic growth and natural resource scarcity; endogenous growth, with increasing returns; and “development traps,” including “poverty traps.” These “traps” can arise when there are multiple potential long-term steady-state equilibria, some of which have notably less growth and per-capita utility than others (Azaraidis and Stachurski 2005).

In this paper our goal is to shed light on the possibility of environmental poverty traps due to interactions between the impacts of climate change, and increasing returns in the development of “clean-technology” production sectors. We combine elements of the literature on growth with natural capital, and growth with increasing returns and potential poverty traps. We use a simple specification in which the economy can produce a single homogeneous consumption good with two different technologies. In the “old” sector, the technology has global diminishing returns to scale and depends on the use of fossil energy that gives rise to long-lived, damaging climate change. In the “new” sector, the technology has convex-concave production and is not dependent on the polluting energy input.

If the new sector does not grow fast enough to move through the phase of increasing returns, then the economy may either linger at a low level of income indefinitely or it may achieve greater progress but then get driven back down to a lower level of income by environmental degradation. Stimulating growth in the new sector thus is one key element for avoiding an environmental poverty trap and achieving higher, sustained income levels. Because of increasing returns in the sector, moreover, there may be a role for more interventionist industrial policies to complement conventional measures of environmental externality pricing. In this respect, the paper complements and expands upon the framework in Acemoglu et al. (2012).

In the next section of the paper we provide additional background on the motivation for the paper and our analytical approach. In the third section we lay out our conceptual model. We note there that while the structure of the model is fairly simple, analytical solutions remain elusive given the number of state variables in the model (two capital stocks and the stock of accumulated greenhouse gases (GHGs) in the environment). To obtain information on the characteristics of the efficient growth paths under different assumptions, we turn instead in the fourth section of

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the paper to numerical simulation experiments. Although the model parameters are picked arbitrarily and do not reflect the situation in any actual economy, the simulations serve as a numerical equivalent of comparative dynamics exercises with analytical models to show how solution paths vary with different parameters. The fifth and final section summarizes our findings and comments on important extensions of the research.

2. BACKGROUND

One line of development in growth models has considered connections among natural resources – represented as stocks of natural capital (Brock and Taylor 2005), economic development, and poverty (Barbier 2006, 2010; Dasgupta 2010). One important insight from the environment-and-growth literature is that with interactions between two stocks (natural and built capital), the long-term path of the economy may not be unique even with well-behaved concave production possibilities. Krautkramer (1985) showed that when resource depletion affects utility directly as well as the opportunity cost of material inputs to production, the economy may converge toward a steady state with depleted natural capital, even though this implies low long-term utility, if the opportunity cost of reversing past resource depletion is too high. Lopez (2010) shows that if the negative impact of industrialization on a natural resource stock is not too large, then industrialization will not threaten sustainability of the resource even if, as is assumed in the model, the natural resource is subject to open access. However, in less favorable circumstances that are identified in the analysis, expansion of the industrial sector will lead to resource depletion.

While this strand of growth theory has developed largely with the field of environment and natural resource economics, more mainstream growth theorists began challenging the implication from the basic Ramsey/Solow model that long-term growth is determined due largely by exogenous factors such as disembodied technical change. Endogenous growth theory holds that factors such as endogenous technical innovation and spillover productivity effects from human capital increases explain long-term growth, in particular its ability to persist even as capital accumulates since the abovementioned effects offset tendencies toward diminishing marginal returns to investment.

An important branch of this theory has been concerned with the impacts of increasing returns, if not globally then over a fairly wide range of values for per-capita capital accumulation (Romer 1986, 1994). This pattern could be the result of e.g. limited availability of some technology-specific input such that, as the input becomes more available, a higher-productivity technology can replace a lower-productivity one. If the aggregate per-capita production function is convex and then concave, then multiple equilibria are possible and characterization of the optimal growth paths becomes substantially more complex (Dechert and Nishimura 1983).

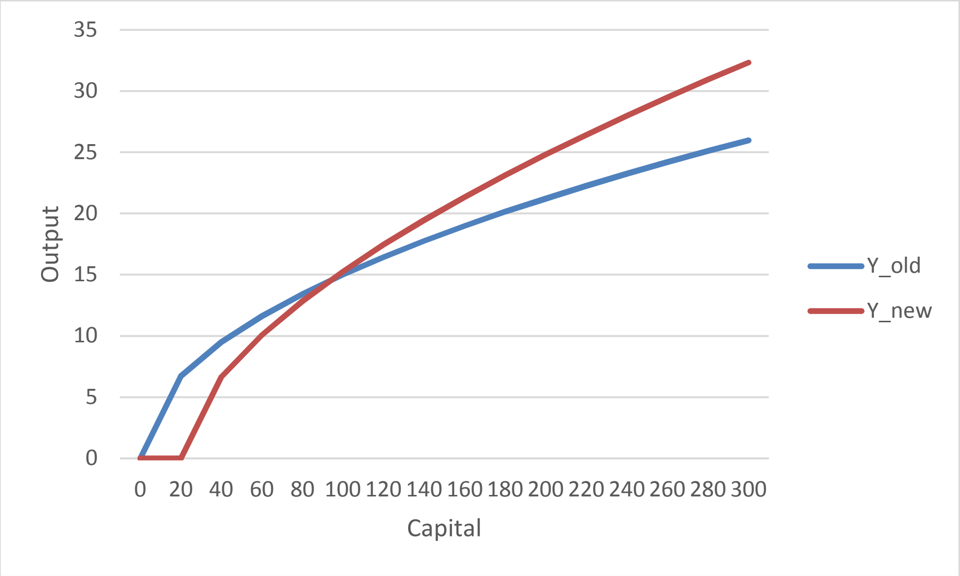
An important example of such multiple equilibria is the existence of a "poverty trap" (Azariadis and Stachurski 2005). The issue stems from multiple equilibria at different stages of development (see for example Graham and Temple 2006). Convergence to a higher steady state is associated with knowledge and human capital accumulation and adoption of new technologies. Conversely, insufficient human capital accumulation is one important reason why a poverty trap could arise. This could be also heterogeneous quality of labor due to income inequality. For example, low income families may suffer from malnutrition and as result cannot supply high quality labor (Gong, Li, Wang, and Zou, H. 2010). Fiaschi and Lavezzi (2007) consider technological spillovers, applying a convex-concave production function, and conclude that inability to adopt modern technologies results in a poverty trap.

The literature on environmental resources and poverty traps is sparse but growing. Antoci, Galeotti, and Russu (2011) consider the potential for poverty traps with open-access natural resources. Prieur, Jean-Marie, and Tidball (2013) consider how quantitative limits on emissions of irreversible pollutants may avoid long-term economic reversal. Fodha, M., & Seegmuller, T. (2013) connect environmental quality and poverty trap and introduce the term "environmental poverty trap". However, Bassetti, T., Benos, N., & Karagiannis, S. (2013), analyzing joint distribution of per-capita income and carbon dioxide emissions, do not find evidence so far that there is an environmental poverty trap in the case of greenhouse gas emissions.

Figure 1 presents a stylized economy which has the possibility to implement two distinct technologies. (Similar stylized representations of technologies can be found in e.g. Azaradis 1996, Kraay and Raddatz 2007.) What we call the "old" sector production function in Figure 1 has constant returns to scale and is strictly concave in per-capita labor. In contrast, the "new" production function cannot generate positive output until capital attains a minimum scale.

This minimum scale of sector level capital is a simple way to reflect more complex "set-up" requirements at the aggregate sector level. Those in turn can reflect both the sector level investment needed to produce specialized intermediate or capital goods, and the investment needed to build up a critical mass of human capital within the available work force. The set-up problem thus is a case of imperfectly mobile factors of production, i.e. physical or human capital from the old sector cannot be instantaneously and costlessly converted for use in the new sector. Mayer-Foulkes (2008) provides an example from México of a double-peaked distribution for education, implying an obvious lack of homogeneity in the labor force, and connects the possibility of a poverty trap with insufficient supply of more advanced human capital. Semmler and Ofori (2007) connect information on twin-peak income distributions in developing countries to the presence of local increasing returns.

Figure 1. Production functions for the new and the old sectors



3. THE MODEL

Throughout the paper we use the subscript *1* for the "old" sector with polluting production technology, and *2* for the "new" sector with clean production technology. We use the following notation:

K_i = total stock of capital ($i = 1,2$)

I_i = gross investment

E_i = energy input to production

C = total consumption of the composite output

$u(C)$ = utility from consumption; we assume $u(C) = \ln(1 + \gamma C)$ for some $\gamma > 0$

X = stock of greenhouse gas emissions in the environment

$D(X)$ = economic damage caused by greenhouse gas accumulation; we assume $D(X) = \frac{1}{1+DX}$

For some parameter $D > 0$.

ρ = rate of utility discounting over time

δ = capital depreciation rate

p_i = real unit cost of energy input, in terms of the composite good as *numeraire*

B_i = scale parameter for production; $B_i > 0$

ε_i = energy-capital ratio

η = elasticity of gross output with respect to capital input in Sector 1; $0 < \eta < 1$

α = elasticity of gross output with respect to capital input in Sector 2; $0 < \alpha < 1$

μ = proportional rate of decay in accumulated greenhouse gas emissions X; $\mu > 0$

Considering first the old sector, to have as simple a model as possible while still being able to address the problem in a nontrivial way, we make the following assumptions:

A1) Production in the old sector has fixed proportions between capital and energy, with ε_1 = energy input per unit of capital.

A2) Gross output in the absence of climate change is strictly concave in the capital – energy bundle defined by A1, and is given by $B_1 K_1^{\eta}$.

A3) The unit cost of energy in the old sector, p_1, is constant, with $1 - p_1\varepsilon_1 > 0$.

With these assumptions, we can write net output in the absence of climate change as

$$B_1 K_1^{\eta} - p_1 E_1 = B_1 K_1^{\eta} - p_1 \varepsilon_1 K_1$$

A4) Net output with climate change damage is given by

$$F(K_1, X) = B_1 K_1^{\eta} D(X) - p_1 \varepsilon_1 K_1 \tag{1}$$

where the damage term *D(X)* satisfies

$$D(X) = \frac{1}{1+DX} \tag{2}$$

with $D > 0$. In this formulation, we assume that climate change reduces gross output for any bundle of inputs, but does not increase the real cost of energy supply.

From (1) and (2), we can show that $F(K_1,X) > 0$ if and only if

$$X < \frac{B_1 K_1^{\eta} - p_1 \varepsilon_1 K_1}{D p_1 \varepsilon_1 K_1}$$

This defines a feasible set of initial values for $K_1(0)$ and $X(0)$, which we assume is satisfied.

A5) The utility function $u(C)$ satisfies

$$u(C) = \ln(1+\gamma C) \tag{3}$$

for some parameter $\gamma > 0$. Note that u is increasing and strictly concave, with $u(0) = 0$, $u'(0) = \gamma$, and $u'(C) \rightarrow 0$ as $C \rightarrow \infty$.

A6) The GHG concentration in the atmosphere decays at a constant rate μ; the concentration increases in proportion to the rate of energy use in the old sector.

If we assume without loss of generality that the proportionality constant for additions to the GHG concentration is equal to 1, then by A1 and A6 we can write

$$\dot{X} = -\mu X + \varepsilon_1 K_1 \tag{4}$$

Accompanying this stock equation is the standard equation of motion for capital,

$$\dot{K_1} = -\delta K_1 + I_1 \tag{5}$$

Putting the pieces together, we can state the optimal growth problem with Sector 1 as

$$\max \int_0^{\infty} e^{-\rho t} u(C) dt$$

subject to (1) – (5). Note that from (1) and (2),

$$C + I_1 = B_1 K_1^{\eta} \frac{1}{1+DX} - p_1 \varepsilon_1 K_1 \tag{6}$$

To solve this problem we can introduce the current value Hamiltonian

$$H = u(C) + \lambda_1 \dot{K_1} + \xi_1 \dot{X} \tag{7}$$

Using (4) – (6), the co-state variables for K_1 and X respectively satisfy

$$\dot{\lambda_1} = \rho\lambda_1 - \frac{\partial H}{\partial K_1} = (\rho+\delta)\lambda_1 - \xi_1\varepsilon_1 - u'(C) B_1 \eta K_1^{\eta-1} \frac{1}{1+DX} - p_1\varepsilon_1 \tag{8}$$

$$\dot{\xi_1} = \rho\xi_1 - \frac{\partial H}{\partial X} = (\rho+\mu)\xi_1 - u'(C) K_1^{\eta} \frac{-B_1 D}{(1+DX)^2} \tag{9}$$

An interior optimal investment choice satisfies

$$\frac{\partial H}{\partial I_1} = 0 => u'(C) = \frac{\gamma}{1+\gamma C} = \lambda_1 \tag{10}$$

Eq. (10) is the standard result that the marginal utility of consumption should equal the shadow value of new capital. In (8), however, we see that the shadow price includes the marginal shadow cost of GHG accumulation times the rate at which accumulation of K_1 also adds to GHG emissions, ε_1 (see (4) above). Writing out the solution to (9) in integral form, we obtain[2]

$$\xi_1(t) = e^{(\rho+\mu)t} \int_t^{\infty} e^{-(\rho+\mu)s} [\ u'(C) K_1^{\eta} \frac{-B_1 D}{(1+DX)^2}] ds < 0$$

Thus the shadow cost of GHG accumulation is the integral of the incremental losses in future output from additions to future stocks of GHG due to increased emissions today, weighted by the marginal utility of consumption, with an "effective discount rate" of (ρ + μ).

Next, we specify the characteristics of the "new" sector.

A7) Production in the new sector has fixed proportions between capital and energy, with ε_2 = energy input per unit of capital.

A8) Gross output in the new sector is given by $B_2(K_2 - \overline{K_2})^{\alpha}$ for $K_2 \geq \overline{K_2} > 0$, using A7 to eliminate its dependence on the energy input. This output is not sensitive to climate change.

A9) The unit cost of energy in the new sector, p_2 is constant. Moreover, energy used in the new sector does not contribute to GHG emissions in the atmosphere.

With these assumptions, we can write net output in the new sector as

(11) $$G(K_2) = B_2 \max\{0, (K_2 - \overline{K_2})^{\alpha} - p_2 E_2\} = B_2 \max\{(0, (K_2 - \overline{K_2})^{\alpha} - p_2 \varepsilon_2 K_2\}$$

Obviously we are making very strong assumptions about the new sector – that it relies entirely on carbon-free energy and that its output is not affected by climate change. However, by starting with this simple case we can make headway in understanding the dynamics of the model prior to considering more complex and realistic formulations.

Assumption A8 says that output in the new sector requires capital investment at least as large as some minimum quantity $\overline{K_2} > 0$. This minimum capital requirement is a form of set-up cost that introduces a nonconvexity in production through increasing returns to scale, which is an important part of the story we want to explore in the paper. As noted above, we can justify such a sector-level nonconvexity in various ways. One justification is that the economy must establish specialized facilities for investment in the new sector, or training capacities for workers employed in the sector (though we are not modeling labor choices in this model).

4. SOLUTION PROPERTIES – NUMERICAL EXPERIMENTS

In principle, we can set $\dot{X} = \dot{K_1} = \dot{\lambda_1} = \dot{\xi_1} = 0$ and use (4) – (6) and (8) – (10) to solve for steady-state values of $(X, K_1, \lambda, \xi, I, C)$, and more importantly, how these values change with shifts in key exogenous parameters. In practice, the nonlinearities in this system appear to preclude such an algebraic approach. Instead, we will use numerical simulations to explore the steady-state properties of the system. As noted, the numerical values chosen for key parameters are arbitrary and are not intended to represent the actual properties of a specific economy. Instead, the numerical experiments should be seen as the analogue of analytical comparative dynamics exercises with respect to changes in the exogenous parameters.

We adopt the following values for the parameters indicated across all scenarios:

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[2] This transformation relies on the transversality condition $\lim_{t \to \infty} e^{-(\rho+\mu)t}\, \xi_1(t) = 0$.

- Initial stock of capital in the old sector and in the new sector: $K_1(0) = 5$, $K_2(0) = 0$;
- Initial stock of greenhouse gas emissions in the environment: $X(0) = 1.2$;
- Capital depreciation rate: $\delta = 0.05$;
- Rate of emissions concentration decay in the atmosphere: $\mu = 0.03$;
- Utility scaling coefficient: $\gamma = 0.05$;
- Production functions coefficients for the old and the new technologies: $B_1 = 1.5$ and $B_2 = 1.1$;
- Production function exponents: $\eta = 0.5$ (the old sector) and $\alpha = 0.6$ (the new sector).

We single out for variation the four parameters shown in Table 1:

Table 1. Values of parameters across different scenarios

Scenario	**1**	**2**	**3**	**4**	**5**
Emissions intensity in old sector (ε_1)	0.02	0.02	0.02	0.05	0.02
Damage scaling parameter (D)	0.2	0.1	0.2	0.2	0.2
Minimum capital needed in new sector for production ($\overline{K_2}$)	20	20	10	10	20
Utility discount rate (ρ)	0.015	0.015	0.015	0.015	0.03

Production functions for the old and the new sectors are as presented in Figure 1 above. If the initial stock of capital is relatively small, then the old technology dominates the new one. However, when capital stock exceeds 100, the new technology is preferable. Moreover, the old sector is vulnerable to climate change, while the new sector is not. The net productivity of the old sector declines along with accumulation of carbon in the atmosphere. Graphically, this implies a rotation of the production function down toward the horizontal axis.

In the first scenario, only the old sector is active. This is because a relatively low rate of capital accumulation does not allow the economy to save enough resources to cover the set-up cost for the new sector (set at $\overline{K_2} = 20$). This scenario demonstrates the limits of economic growth based just on expansion of old polluting sector, which we can call "brown growth." Table 2 below presents results for the numerical solution over 25 time periods.

Table 2. Scenario 1 results

Time period	0	5	10	15	20	25
Consumption	2.56	3.10	3.06	2.91	2.76	2.65
Capital in the old sector	5.00	6.52	7.03	7.56	8.47	9.51
Emissions	0.10	0.13	0.14	0.15	0.17	0.19
Emission Stock	1.10	1.49	1.92	2.33	2.74	3.20

The "brown economy" reaches the highest consumption around the 5th period and then declines. Capital accumulation almost doubles the capital stock over 25 years, yet consumption is only marginally larger than in year zero. Accumulation of capital is not sufficient to ensure productivity needed for continues consumption growth. The economy further shrinks to reach a lower steady state beyond the 35th period. The economy would avoid such a brown poverty trap only if emissions flow attributed to initial stock of capital is lower than emissions decay. The economy could then converge to a stable steady state with some growth in consumption, which we call a "brown trap." For reference when comparing other scenarios to this one, the total discounted welfare over the optimization period for this scenario is about 192.

The second simulation has the same parameters, except the old sector is less vulnerable to climate change (D=0.1, i.e. half of the value in scenario 1). Once again, only the old sector is active in the optimal path. In this case, consumption increases up to 15th period (see Table 3). A higher value is attained for total discounted welfare, 202, which can be attributed to the lower climate change damage (so more resources are available for consumption), as well as slightly higher accumulation of capital. However, it still becomes more difficult to sustain economic growth since the emissions stock keeps building up, and additional damage eventually "overrides" the effects of additional investment and production. The economy declines toward a "brown trap."

Table 3. Scenario 2: lower climate damage

Time period	0	5	10	15	20	25
Consumption	1.94	3.40	4.08	4.18	4.08	4.02
Capital in the old sector	5.00	10.07	13.06	14.87	16.35	17.30
Emissions	0.10	0.20	0.26	0.30	0.33	0.35
Emission Stock	1.10	1.63	2.48	3.43	4.41	5.37

The only way to avoid a brown trap in the model is for there to be a transition to use of the new technology. This does not occur in the first two scenarios given the baseline level of minimum capital stock $\overline{K_2} = 20$. In scenario 3 we reduce the minimum capital stock to $\overline{K_2} = 10$.

Table 4. Scenario 3: lower set-up cost

Time period	0	5	10	15	20	25
Consumption	1.84	2.61	2.07	3.48	4.78	6.01
Capital in the old sector	5.00	11.89	9.37	7.25	5.61	5.36
Emissions	0.10	0.24	0.19	0.15	0.11	0.11
Emission Stock	1.10	1.67	2.46	2.91	3.11	3.16
Capital in the new sector	0.00	0.00	8.66	16.18	27.50	39.85

Table 4 illustrates gradual substitution out of the old technology into the new one. By the 25th period consumption reaches the highest value among the three scenarios. Adoption of the new technology increases productivity of the economy while avoiding the adverse impacts of climate change. Total discounted welfare, 206, is higher relative to scenario 1 (192), though it is only slightly larger than Scenario 2 (202). This reflects that some consumption is sacrificed initially to overcome the setup cost of the new technology.

Figure 2 illustrates the GHG stock accumulation for three scenarios considered so far. By the 25th period, the economy in Scenario 1 with only the old sector accumulates the same GHG stock as the economy in Scenario 3 with both the old and the new sectors (and the same damage parameter). However, the economy in transition to the new technology is less vulnerable to climate change. High economic growth continues beyond the 25th period, with continued decline of the share of the old sector and simultaneous reduction of the GHG stock[3].

Figure 3 illustrates capital accumulation for the first and the third scenarios. Anticipation of the future opportunity to invest into the new and more productive sector creates incentives for accelerated accumulation of capital in the old sector during the first six time periods in Scenario 3, given the lower set-up cost ($\overline{K_2} = 10 \text{ versus } 20$). Then, starting from period six, the economy in Scenario 3 begins accumulation of capital in the new sector in order to reach a threshold level of gross output sufficient to cover the set-up cost in the future. The new sector starts producing net output only in 12th period and then quickly picks up. Building up the necessary output potential to begin deployment in the new sector, the economy initially builds up the old sector and accumulates GHG faster than in first scenario (see Figure 2), but then this process reverses around the 25th period and the GHG stock in Scenario 3 begins to decline, while in Scenario 1 it continues to build up.

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[3] More detailed analysis of a long-run economic growth requires introduction of exogenous increase of productivity in both sectors. Without exogenous increase of productivity, the old sector will always coexist with the new one and emissions flow will be always in the neighborhood of emissions decay.

Figure 2. Comparison of GHG accumulation paths

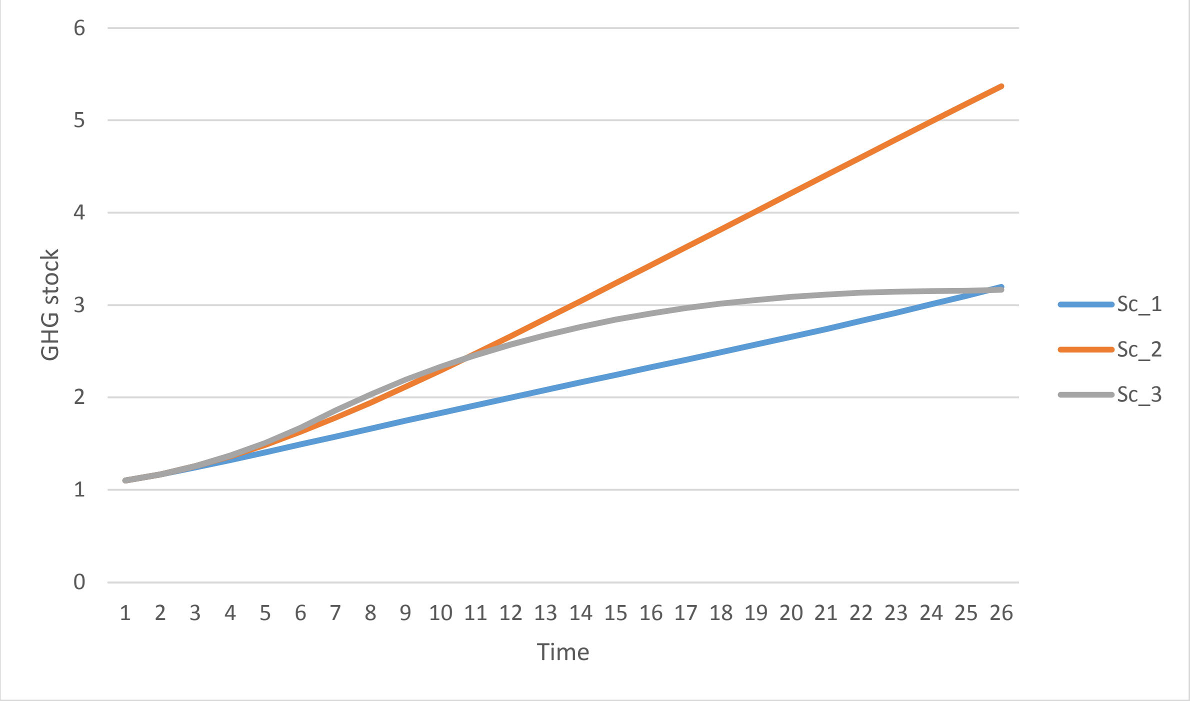
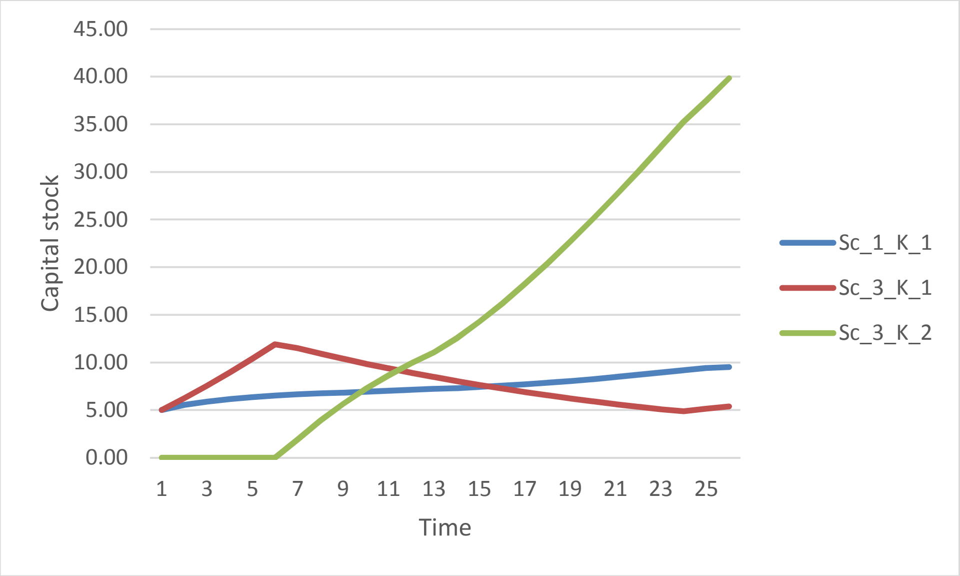


Figure 3. Capital accumulation in the old and the new sector



The carbon intensity of the old sector also plays an important role determining an optimal process of sectoral substitution. For Scenario 4 we assume ε_1 =0.05, versus the value in previous scenarios of 0.02. With a more energy-intensive old sector, GHG accumulation also occurs more quickly. We continue to assume the lower value for setup cost. In this case, capital accumulation in the new sector begins earlier to mitigate the adverse impacts of climate change.

Table 5. Scenario 4: Higher carbon intensity in the old sector and lower set-up cost

Time period	0	1	2	3	4	5	15	20	25
Consumption	0.80	0.85	0.91	0.98	1.07	1.23	3.36	4.35	5.32
Capital in the old sector	5.00	5.79	6.48	7.14	7.73	8.20	5.56	4.31	3.42
Emissions flow	0.25	0.29	0.32	0.36	0.39	0.41	0.28	0.22	0.17
Emissions Stock	1.45	1.66	1.90	2.16	2.46	2.77	5.21	5.65	5.78
Capital in the new sector	0.00	1.51	2.93	4.33	5.69	6.99	19.96	29.42	40.41

By the 25th period the economy exhibits somewhat lower consumption and higher GHG emissions stock than in Scenario 3. The size of the new sector is approximately the same as in Scenario 3, but the size of the old sector is notably smaller, reflecting the lower long-term return to investment when climate damages are accumulating more quickly. The total discounted welfare for Scenario 4 is 194, less than in Scenario 3 (206). This is because of the more rapid accumulation of GHG damages with a more energy-intensive old sector. However, the case (not shown here) with higher pollution rate ($\varepsilon_1 = 0.05$) and higher set-up cost, so that the new sector is not active, yields significantly lower welfare at 181. Thus, our conclusion about how lower cost for new technology adoption improves welfare continues to hold given a relatively higher emission intensity for the old technology.

As expected, the discount rate also plays an important role determining efficient growth. For an economy with relatively high start-up cost for the new sector, a higher discount rate implies more rapid initial capital accumulation and relatively lower consumption in the very beginning (from period 0 to period 4), then higher consumption from period 5 to about period 30 (Figure 5).

Emissions in the scenario with a higher discount rate are consistently higher until the 48th period (Figure 6). The economy with relatively lower discount rate accumulates lesser pollution stock and has relatively more resources to slow down inevitable consumption decline.

Figure 4. Capital accumulation with more carbon intensive old sector and lower start-up cost

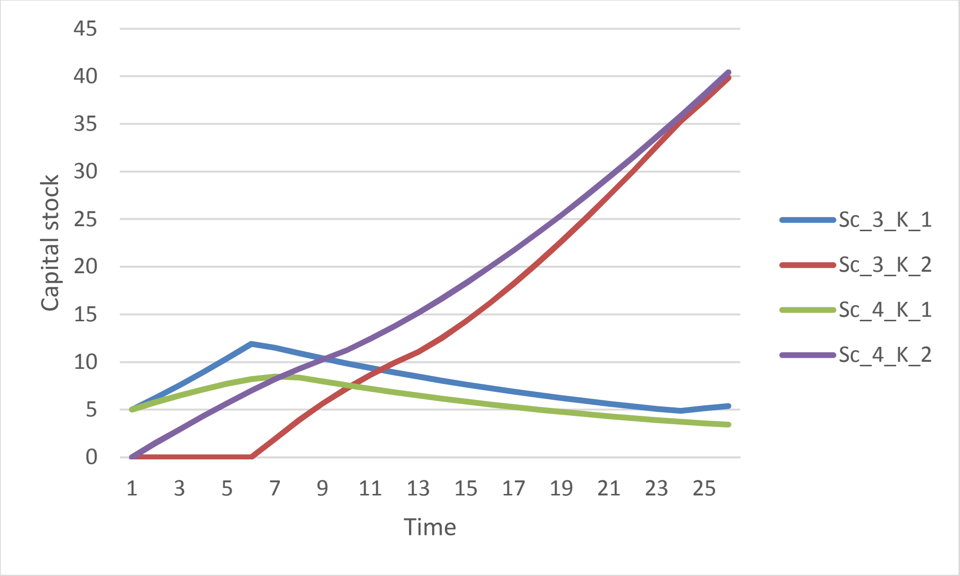


Figure 5. Consumption for different discount rates ($\overline{K_2} = 20$)

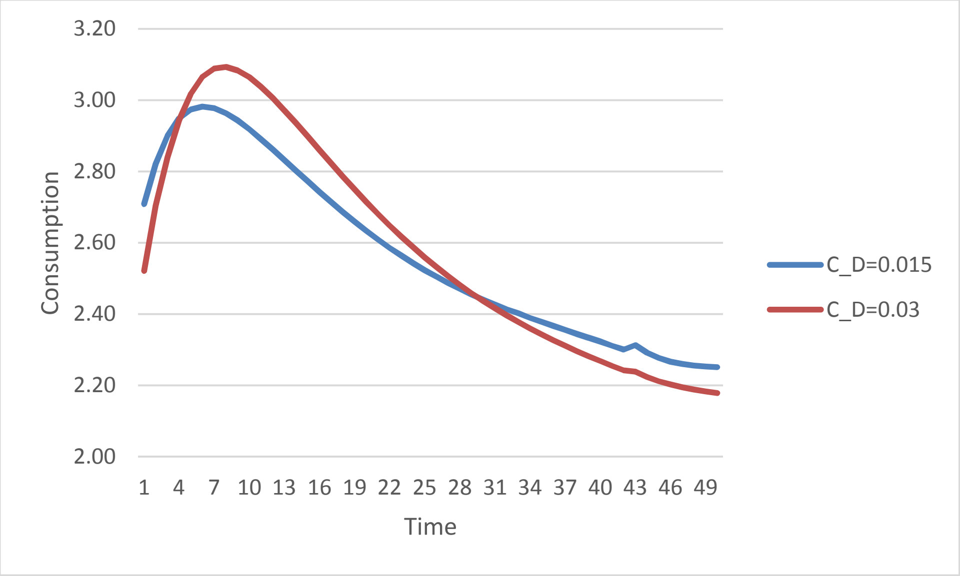
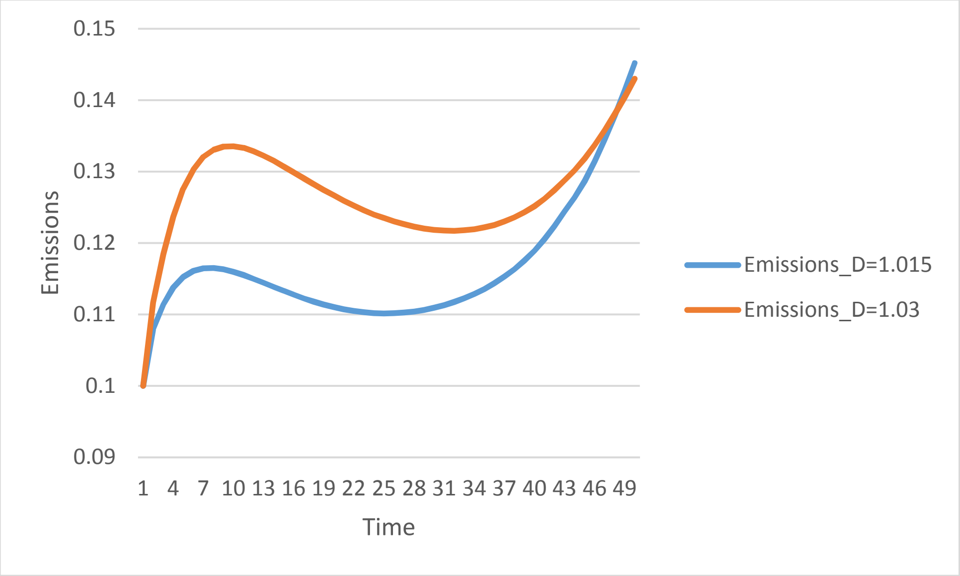


Figure 6. Emissions accumulation for different discount rate



For an economy with relatively low start-up cost ($\overline{K_2} = 10$), in which the new sector develops, a higher discount has only a slight effect on the optimal trajectory. Nevertheless, higher discounting slows down capital accumulation in the new sector. In the medium term, with higher discounting the accumulation of capital in the old sector is about 2% higher and pollution is about 3% higher. In the long-run, accumulation of the new capital is 10% lower and the pollution stock is about 2% higher.

5. CONCLUDING REMARKS

In this paper we have taken an initial step toward better understanding how the incentive to decarbonize production, if the social cost of GHG emissions is taken into account, interacts with barriers to industrial transformation posed by imperfectly malleable inputs and set-up costs. We show that such barriers, which introduce a nonconvexity in the aggregate production possibility set, can lead to an efficient path without extensive decarbonization and with stagnant growth. As expected, lower set-up costs can lead to an efficient growth path incorporating introduction of the new low-carbon technology. This is also more likely the greater the carbon intensity of existing production (since damages accumulate more quickly), the more damaging accumulated emissions are for growth, and the lower the rate of utility discounting (which increases the present value cost of long-term losses due to climate change).

Our results are broadly similar to those of Krautkraemer (1985) and others who have shown that both environmentally degraded and nondegraded growth paths can be efficient. In that setting, however, a key determinant is the initial state of the environment – if it is sufficiently degraded then the opportunity cost (in terms of foregone consumption) of trying to move back toward a nondegraded environment is higher than the benefit. In our framework, set-up costs can impede a move toward a low-carbon industrial structure even if the initial state of the environment is relatively good.

Our results also echo the point made by Acemoglu et al (2012) that in the presence of a nonconvexity in the economy, efficient pricing of the marginal carbon externality (our co-state variable ξ) may not in itself be sufficient to drive the economy to the maximally efficient growth path. In Acemoglu et al the barrier is a limit on the malleability and mobility of high-skill human capital for technological innovation in low-carbon versus higher-carbon production. The policy implication there is that high-skilled workers may need to have salary premiums to be attracted to innovate in the nascent "green sector." In our framework, the barrier can arise from that or other specialized factor immobility. In e.g. Rodrik (2008), industrial policy is advocated as a way to address coordination problems in the face of economies of scale that need to be reaped for effective development. In our setting, a lower set-up cost can overcome the effect of the nonconvexity and can be welfare-improving. This leads us to speculate that subsidies of start-up cost may be welfare-improving, as well. However, further work is needed to evaluate this possibility, especially given the caveats related to the practical difficulties governments face in prudently and effectively undertaking such efforts.

The analytical framework we have used is a very simplified one that can be (and is being) generalized in several ways in ongoing work. Especially useful extensions include developing a more dynamic representation of the set-up problem (e.g. through adjustment costs that limit the speed at which the new sector can be built up), and extending the model to deal with both environmental uncertainties (affecting investment returns in the old sector) and technological uncertainties (affecting investment returns in the new sector).

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